two scintillation spectrometers in coincidence it was however possible to show that the two lines are in cascade. The 250-kev line might be identical with the one reported by Temmer and Heydenburg,[4] found by Coulomb excitation of an odd Hf isotope.

The proposed decay scheme appears in Fig. 2. The intensity ratio of the 72-kev and 208-kev lines is in agreement with the value expected from the theoretical lifetime relation.[5] On the same basis, however, the relative intensity of the 321-kev line is much larger than that expected for an $E3$ transition. No transition was observed between the 250-kev and 113-kev levels.

According to their ft value, spin and parity change, the three β spectra can be classified as allowed, $\Delta I=0$, no (176 kev); first forbidden $\Delta I=1$, yes (384 kev); and first forbidden $\Delta I=1$, yes (497 kev). The spin of the ground state of Hf^{177} is either $\frac{1}{2}$ or $\frac{3}{2}$.[6] The shell model predicts a $p_{\frac{1}{2}}$ configuration,[7] which is used as a basis for the tentative spin assignment in Fig. 2. According to McGowan's angular correlation experiments[2] the 208-kev—113-kev dipole-quadrupole cascade involves a spin change of $+1$ and -2 units and a spin 7/2 for the intermediate level (113 kev). A spin 5/2 for this level, however, would not be in serious contradiction with McGowan's results. One finds then a spin $\frac{3}{2}$ and even parity for the ground state of Lu^{177}, which is not in contradiction with the predictions of the shell model.

We would like to acknowledge the interest of Professor Jesse W. M. DuMond in this work. We are indebted to Mr. E. Hatch and Mr. P. Snelgrove for their help during the measurements.

[4] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **94**, 1399 (1954).
[5] R. Montalbetti, Can. J. Phys. **30**, 660 (1952).
[6] E. Rasmussen, Naturwiss. **23**, 69 (1935).
[7] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).

PHYSICAL REVIEW VOLUME 97, NUMBER 1 JANUARY 1, 1955

Angular Distribution of Gamma Rays from Proton Capture in B^{11}

H. E. GOVE AND E. B. PAUL
Physics Division, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada
(Received September 2, 1954)

The γ-ray yield at 90° from the bombardment of B^{11} by protons shows resonances for proton energies of 0.67, 1.4, and 2.7 Mev. The angular distributions of the two γ rays of high energy, $\gamma_0\sim17$ Mev and $\gamma_1\sim12$ Mev, have been measured at these resonances to obtain evidence concerning the spins and parities of the excited nucleus. The evidence favors $2-$ for the 0.67-Mev resonance, $1-$ for that at 1.4 Mev, and $2+$ at 2.7 Mev, but these assignments cannot be made with certainty.

I. INTRODUCTION

THE most recent and most complete investigation to date on the capture gamma radiation from proton bombardment of B^{11} is that of Huus and Day.[1] A brief summary of this work follows. Using a sodium iodide scintillation counter they have examined the gamma-ray spectrum and find the capture gamma rays which occur in a direct transition to the ground state of C^{12} and in a cascade through the 4.44-Mev level in C^{12}. Yield curves for the transition to the ground state ($h\nu\sim17$ Mev) and to the first excited state at 4.44 Mev ($h\nu\sim12$ Mev) were measured at 90° at proton energies from 0.15 Mev to 2.8 Mev. Cross sections for the various gamma rays were also measured. In addition to the well-known resonance at 0.163 Mev, resonances were observed at 0.675 with $\Gamma=0.33$ Mev and at 1.388 with $\Gamma=1.27$ Mev. Spins and parities of these states are deduced from these measurements and measurements of the $B^{11}(p,\alpha)Be^8$ reaction made by Beckman, Huus, and Zupančič[2] to be $2-$ or $3+$ for the 0.675 resonance and $1-$ for the 1.388 resonance. The latter result is based primarily on single-particle limit[3] and radiation width[4] considerations. In addition, the yield curve for a 2.13-Mev gamma ray produced in an inelastic scattering reaction involving the first excited state of B^{11} was observed and showed a resonance at 2.664 Mev with a width of 48 kev. A comprehensive list of references to previous work in this field is contained in the paper of Huus and Day.

Recently some measurements on the angular distributions of the ground and first excited state gamma transitions have been reported[5] by Givin *et al.*

The work to be reported here comprises measurements of the yield curve at 90° to the proton beam of the capture gamma rays in the range of proton energies between 0.55 and 2.85 Mev. In addition, their angular distributions have been measured at several energies in this range.

[1] T. Huus and R. B. Day, Phys. Rev. **91**, 599 (1953).
[2] Beckman, Huus, and Zupančič, Phys. Rev. **91**, 606 (1953).
[3] T. Teichmann and E. P. Wigner, Phys. Rev. **87**, 123 (1952).
[4] J. M. Blatt and V. F. Weisskopf *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), first edition, p. 627 S. Moszkowski, Phys. Rev. **89**, 474 (1953).
[5] Givin, Farney, Hahn, and Kern, Phys. Rev. **95**, 641(A) (1954).

II. BEAM AND TARGET ARRANGEMENT

The Chalk River electrostatic generator provided the source of bombarding protons. The protons were analyzed in momentum by a 90° magnet whose field was held constant by a proton resonance fluxmeter. A pair of tantalum slits at the exit of this magnet provided a signal to control the corona load and this kept the proton energy constant to about 0.1 percent. The protons passed along a fifteen-foot section of evacuated tubing terminated with a hollow brass cylinder with $\frac{1}{16}$-in. walls containing the target. This arrangement ensured cylindrical symmetry in the gamma-ray absorption. A $\frac{1}{8}$-in. diameter aperture in a 0.02-in. thick tantalum disk located about four feet from the target defined the beam to a spot on the target $\frac{1}{4}$-in. in diameter. Beam currents were normally from five to twenty microamperes.

The target was prepared by mixing finely powdered boron with benzene and spreading evenly on a 0.04-inch tantalum backing and allowing to dry. In the process of drying the powder tended to concentrate

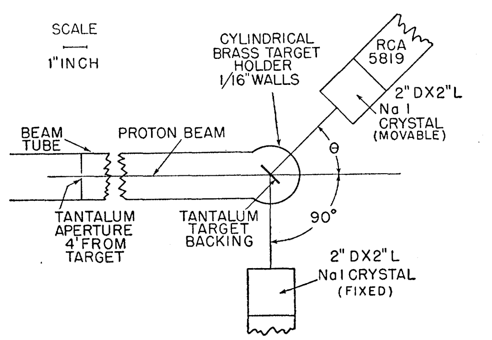

FIG. 1. Schematic diagram of experimental arrangement.

in small patches producing a somewhat nonuniform thickness varying from zero to 200 kev. Later evaporated targets were prepared but most of the work reported here was done with the powder.

The gamma rays were measured in a sodium iodide scintillation counter consisting of a NaI(Tl) crystal 2 in. in diameter and 2 in. long mounted in a polished aluminum case and coupled optically to an RCA 5819 photomultiplier by a short Lucite light pipe. Output pulses were amplified by a linear amplifier and displayed on a thirty-channel pulse-height analyzer. A similar scintillation counter was used as a monitor for angular distribution measurements. The counter subtended a solid angle of about 1 percent. The target and counter arrangements are illustrated in Fig. 1.

III. EXPERIMENTAL PROCEDURE

Both the 90° yield curve and the angular distributions were obtained by recording the complete gamma-ray spectrum on the thirty-channel pulse height analyzer as a function of proton energy or angle. Typical spectra are shown in Figs. 2 and 3. Figure 2 shows

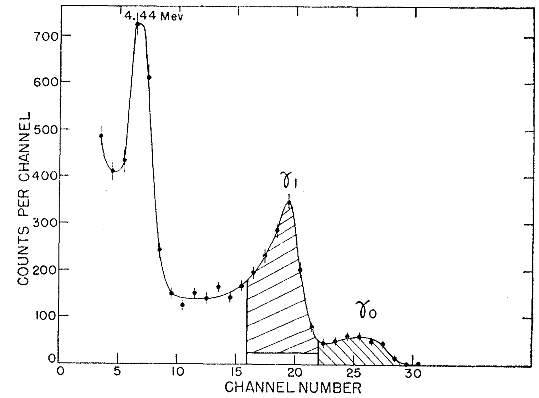

FIG. 2. Spectrum of high-energy gamma rays emitted at the 0.67-Mev resonance in $B^{11}(p,\gamma)$, showing the ground state transition γ_0, the transition γ_1 to the first excited state in C^{12} at 4.44 Mev, and the cascade gamma ray of energy 4.44 Mev. The two shaded areas were taken as proportional to the yields of γ_0 and γ_1 respectively.

the gamma-ray spectrum measured near the 0.68-Mev resonance while Fig. 3 shows the spectrum near the 1.4-Mev resonance. The yield or angular distribution of the capture gamma ray to the ground state of C^{12} ($h\nu\sim 17$ Mev) was obtained by counting only the pulses in channels beyond those corresponding to the transition to the first excited state. However, to measure the yield or angular distribution of this latter gamma ray the contributions from the Compton tail of the ground-state gamma ray must be subtracted. To determine the shape of the gamma-ray spectrum, measurements were made on a single energy gamma ray from the $F^{19}(p,\alpha\gamma)$ reaction, $E_\gamma = 6.13$ Mev, which showed that a long flat portion exists in the spectrum below the pair peaks—the ratio of height of the pair peak to this flat portion being about 3.5 for a crystal 2 in. in diameter and 2 in. long. The results on boron indicate that at gamma energies around 14 Mev this ratio had dropped to about 2.5. It is then only necessary to subtract from the region under the 12-Mev gamma-

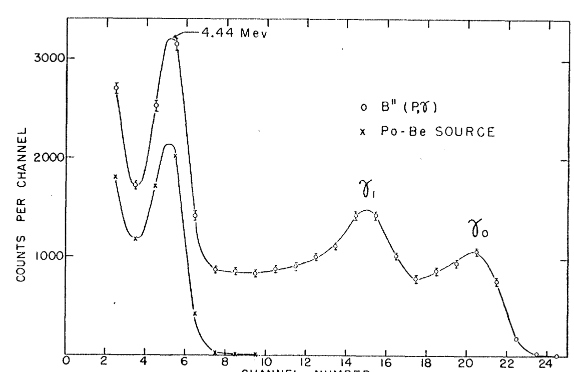

FIG. 3. Spectrum of high-energy gamma rays emitted near the 1.4-Mev resonance in $B^{11}(p,\gamma)$, showing the ground state transition γ_0, the transition γ_1 to the first excited state in C^{12} at 4.44-Mev, and the cascade gamma ray of energy 4.44 Mev. This is compared with the same gamma ray from a Po-Be source.

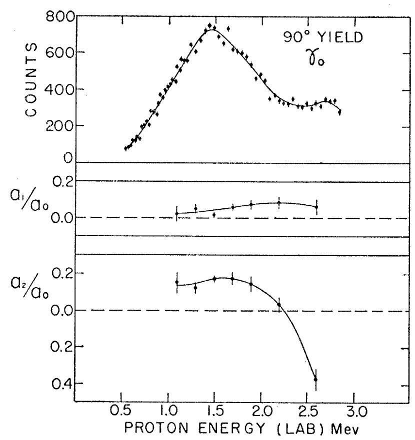

FIG. 4. The upper curve shows the 90° yield curve of gamma rays leading to the ground state of C^{12} from proton capture in B^{11}. The two lower curves show the variation of the coefficients of the Legendre polynomial expansion of the angular distribution of this gamma ray, $W(\theta)=P_0+(a_1/a_0)P_1+(a_2/a_0)P_2$, with proton bombarding energy.

ray spectrum an amount equal to 0.4 times the peak of the 17-Mev gamma-ray spectrum. Figure 2 is a spectrum taken during the 90° yield measurements and the shaded areas show the actual quantity that was taken to be proportional to the yield of the two high-energy gamma rays.

The angular distributions were measured by recording the spectrum at 10 to 20 angles between 0° and 150°. The distributions were measured at nine different energies between 0.8 and 2.6 Mev. A cobalt-60 source which could be placed in the target position was used to check that the angular symmetry was good to one or two percent.

In the yield measurements the beam current incident on the target was measured with a current integrator.[6] Because of the nonuniformity of the target mentioned above, these measurements were subject to more fluctuation than the angular distributions which were measured relative to the monitor counter.

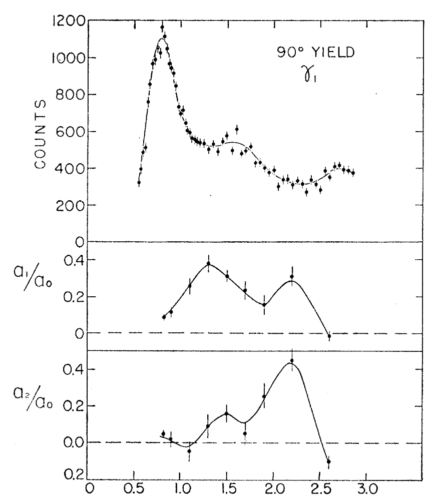

FIG. 5. The upper curve shows the 90° yield curve of gamma rays leading to the first excited state of C^{12} from proton capture in B^{11}. The two lower curves show the variation of the coefficients of the Legendre polynomial expansion of the angular distribution of this gamma ray, $W(\theta)=P_0+(a_1/a_0)P_1+(a_2/a_0)P_2$, with proton bombarding energy.

IV. EXPERIMENTAL RESULTS

The yield curves for the ground-state gamma transition (γ_0) and the transition to the first excited state (γ_1) are shown at the upper part of Figs. 4 and 5 respectively. No correction to the energy has been made for target thickness since it was not accurately known and hence the positions of the resonances on our energy scale are higher than those observed by Huus and Day.

Examples of the observed angular distributions taken at three different energies are shown in Figs. 6, 7, and 8. Figure 6 is the distribution of the capture gamma radiation leading to the first excited state of C^{12} measured at $E_p=0.85$ Mev, corresponding to the 0.68-Mev resonance. The ground state transition is not resonant here and is in fact quite weak, hence its angular distribution was not measured. Figure 7 shows the angular distribution of both the ground-state (γ_0) and the first excited state (γ_1) transition measured near the 1.4-Mev resonance. Figure 8 shows the distributions measured at 2.6 Mev. The angular distributions have been analyzed by the method of least squares in a Legendre polynomial expansion containing the terms P_0, P_1, and P_2. Figure 4 shows the P_1 coefficient a_1/a_0 and the P_2 coefficient a_2/a_0 plotted *versus* proton energy for γ_0 below the 90° yield curve of γ_0, while Fig. 5 shows corresponding data for γ_1. The probable error of each coefficient is given.

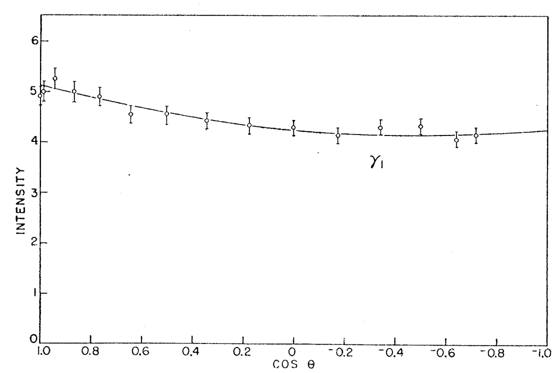

FIG. 6. The angular distribution of the gamma ray (γ_1) leading to the first excited state in C^{12}, taken at a proton energy corresponding to the 0.67-Mev resonance. The smooth curve is a least-squares fit to a series of Legendre polynomials up to P_2.

V. DISCUSSION

Theoretical expressions for (p,γ) angular distributions have been given recently by Biedenharn and Rose[7]

[6] H. T. Gittings, Rev. Sci. Instr. **20**, 325 (1949).

[7] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

and Sharp, Kennedy, Sears, and Hoyle.[8] In calculating the theoretical angular distributions, a spin[9] of $\frac{3}{2}$ and negative parity[10] for the B^{11} ground state has been used. The spin and parity of the ground and first excited state of C^{12} are 0+ and 2+ respectively.[9] We have assumed that contributions from orbital angular momentum greater than two for the incoming particles are negligible and that only radiations of electric or magnetic dipole or electric quadrupole character will be observed with any intensity. Under these circumstances no terms higher than P_2 will occur in the theoretical expressions and, in fact, none higher than P_2 are observed experimentally.

The yield curve for the ground-state gamma transition, Fig. 4, shows a broad resonance at 1.45 Mev on

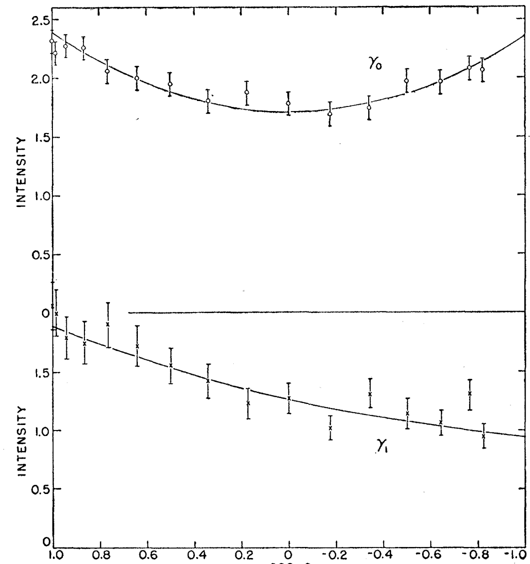

FIG. 7. The upper curve shows the angular distribution of the gamma ray (γ_0) leading to the ground state of C^{12}, and the lower curve that of the gamma ray (γ_1) leading to the first excited state of C^{12}, taken at a proton energy near the resonance at 1.4 Mev. The smooth curves are least-squares fits to a series of Legendre polynomials up to P_2.

our energy scale and probably another one of low intensity at about 2.7 Mev. Both of these also appear in the yield curve for the first excited state gamma transition and in addition a resonance at 0.8 Mev is observed. This corresponds to the 0.67-Mev resonance of Huus and Day.

Since the level at 0.67 Mev is not resonant for either γ_0 or α_0, its spin and parity are expected to be 2− or 3+. The angular distribution of γ_1 is consistent with either assignment. However, arguments based on single-

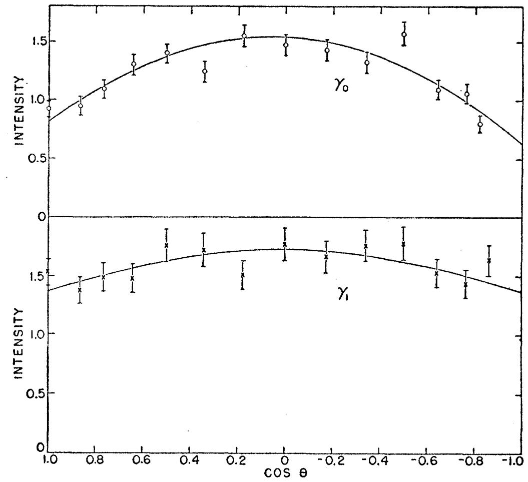

FIG. 8. The upper curve shows the angular distribution of the gamma ray (γ_0) leading to the ground state of C^{12}, and the lower curve that of the gamma ray (γ_1) leading to the first excited state of C^{12}, taken at a proton energy of 2.6 Mev. The smooth curves are least squares fits to a series of Legendre polynomials up to P_2.

particle limits and gamma-ray transition probabilities favor the 2− assignment. In this case the (p,α_1) cross-section measurements of Beckman *et al.*[2] give equal partial widths for proton formation and α_1 decay of 165 kev while those of French[11] give either 290 kev or 40 kev. The single-particle widths calculated according to Lane[12] are 350 kev for *s*-wave protons and 20 kev for *p*-wave which indicates an assignment of 2− for this state. This is consistent with the observed gamma-ray partial width.[4] *Note added in proof.*—The angular distribution of the 12-Mev radiation has been measured by Grant, Flack, Rutherglen, and Deuchars, Proc. Phys. Soc. (London) **67A**, 751 (1954), from 0.4 to 0.67 Mev. Assuming $J=1^-$ for the 1.4-Mev resonance, they conclude that the 0.67-Mev resonance has $J=2^+$.

The level at a proton bombarding energy of 1.4 Mev is resonant for γ_0 and γ_1 as well as for[2] α_0 and α_1 from the $B^{11}(p,\alpha)$ reaction. Hence its spin and parity are almost certainly either 2+ or 1−. When one takes account of all the present experimental evidence, it appears that there is still some ambiguity as to which of these two assignments is correct.

The experimental angular distributions for (p,γ_0) show a small P_1 term (Fig. 4) which rises slowly from a value of $\sim$0.03 at 1.1 Mev to $\sim$0.1 at 2.6 Mev. Hence it appears that interference effects between states of opposite parity which decay by emission of γ_0 are small and may be due to a broad level higher than 2.8 Mev. The P_2 coefficient remains substantially constant at +0.17 from 1.1 to 1.9 Mev (the region covered by the 1.4-Mev resonance) and then drops

[8] Sharp, Kennedy, Sears, and Hoyle, Tables of Coefficients for Angular Distributions, Atomic Energy of Canada Limited, Chalk River Project, AECL-97, December 1953 (unpublished).

[9] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

[10] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 1032 (1953).

[11] A. P. French and G. A. Dissanaike (as quoted by Beckman *et al.*, reference 2).

[12] A. M. Lane, Atomic Energy Research Establishment Report AERE T/R 1289, Harwell, England, January 1954 (unpublished).

rapidly to −0.4 at 2.6 Mev. The constancy over the 1.4-Mev resonance may indicate very little interference between states of the same parity which decay by emission of γ_0 in this region. We shall, therefore, assume that a noninterference analysis of the (p,γ_0) angular distribution at 1.4 Mev is justified.

The theoretical angular distribution for a spin of 2+ for this resonance agrees with experiment for a mixture of channel spin 2 to channel spin 1 of 0.5 for the ground-state gamma transition. There are many parameters in the theoretical expression for the angular distribution of γ_1 for $J=2+$ and no useful conclusions can be deduced. The coefficient of the odd Legendre polynomial P_1 which occurs in the (p,γ_1) distribution (Fig. 5) could also indicate that the state at 1.4 Mev has the opposite parity to that at 0.67 Mev.

The theoretical distribution for $J=1-$ for the ground-state transition also fits the observed distribution if only channel spin 2 participates. Since the channel spin mixture of formation should be independent of the mode of decay, the P_2 coefficient for the first excited state transition γ_1 can be calculated to be 0.02. The observed value is 0.12 which may reflect interference with the other negative-parity state at 0.67 Mev.

Some support for the assignment of 2+ comes from the relative intensities of the two alpha groups at this resonance which favor the transition to the first excited state of Be^8 (assumed 2+) to the ground state 0+ by a factor of 10–20 to one.[2,13] This can be explained in part if the compound level is 2+, since *d*-wave alphas are required for the ground state while *s*-wave alphas could decay to the first excited state. This gives a computed factor of 4 in favor of the latter. If the compound state were 1−, the groups would be expected to have equal intensity from barrier penetrabilities. One cannot regard this as a very conclusive argument.

The arguments favoring an assignment of $J=1-$ for the resonance at 1.4 Mev are the following. From the $B^{11}(p,\alpha_1)$ cross-section measurements of Beckman *et al.*[2] and French and Dissanaike,[11] the proton width of formation is about 1.1 Mev if one assumes it to be larger than the alpha width. This is greater than the single-particle limit for *p*-wave formation.[12] If, however, the alpha width is assumed to be the larger, *p*-wave formation and hence $J=2+$ is permitted. This has the effect of making the partial widths for emission of γ_0 and γ_1 of the order of a few hundred electron volts which is greater than one might expect.[4]

Recent work[14] on the angular distribution of γ_0 at the 0.163-Mev resonance shows an appreciable P_1 term. This may indicate interference between this resonance and the broad 1.4-Mev resonance. Since the 0.163-Mev resonance is very probably 2+,[9] this would imply that the 1.4-Mev resonance is 1−.

Measurements on the $B^{11}(p,\alpha_1)$ distribution up to 1.6 Mev by French and Dissanaike[15] indicate that the 0.67 and 1.4-Mev levels have the same parity. Again this favors 1− for the 1.4-Mev resonance.

The weight of the evidence argues for the assignment of $J=1-$. The variation of the P_1 coefficient in the (p,γ_1) distribution could be rendered compatible with this by invoking the presence of a broad positive parity state underlying both the 0.67- and the 1.4-Mev resonance. This would also explain the P_1 coefficient in the (p,γ_0) angular distribution.

The level at 2.7 Mev appears to be weakly resonant for both γ_0 and γ_1. The large P_2 coefficient of −0.39 which occurs in the angular distribution of the ground-state gamma transition (Fig. 4) is consistent with a spin of 2+ although the possible presence of higher resonances makes the assignment uncertain. Levels have previously been reported in this region by Paul and Clarke[13] at 2.65 Mev with a width of 300 kev, resonant for both α_0 and α_1 in the $B^{11}(p,\alpha)$ reaction, and by Huus and Day[1] at 2.664 Mev with a width of 48-kev resonant for gamma rays of 2.13-Mev energy from the $B^{11}(p,p'\gamma)$ reaction. It is not clear whether or not these three sets of observations correspond to the same level.

VI. SUMMARY

Resonances have been observed in the $B^{11}(p,\gamma)$ reaction at proton energies of 0.67, 1.4, and 2.7 Mev and the angular distributions of the gamma ray to the ground state and first excited state of C^{12} have been measured at several energies in this range. The evidence favors spin and parity assignments of 2− for the 0.67-Mev resonance, 1− for that at 1.4 Mev, and 2+ at 2.7 Mev, but these assignments cannot be made with certainty.

A determination of the parities of the levels at 0.67 and 1.4 Mev would be sufficient to render their spin assignments unambiguous and this might be accomplished by measuring the internal electron-positron pair angular correlation.[16] Another approach would be triple correlation measurements on the 4.44-Mev gamma ray and γ_1. In addition it would be useful to extend the present data beyond 2.7 Mev.

We wish to thank Dr. L. G. Elliott and Mr. W. T. Sharp for their interest in this work and for many instructive discussions of the results.

[13] E. B. Paul and R. L. Clarke, Phys. Rev. **91**, 463(A) (1953).
[14] Craig, Cross, and Jarvis, Phys. Rev. **96**, 825(A) (1954).
[15] A. P. French (private communication).
[16] Devons, Goldring, and Lindsey, Proc. Phys. Soc. (London) **A67**, 134 (1954).